# Novel charmonium-like structures in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra

Xiang Liu[1,2] *†
[1]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
[2]Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China

Zhi-Gang Luo and Shi-Lin Zhu‡§
Department of Physics and State Key Laboratory of Nuclear Physics and Technology
Peking University, Beijing 100871, China
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Stimulated by the new evidence of $Y(4274)$ observed in the $J/\psi\phi$ invariant mass spectrum, we first propose the charmonium-like state $Y(4274)$ as the S-wave $D_s\bar{D}_{s0}(2317) + h.c.$ molecular state with $J^P = 0^-$, which is supported well by dynamics study of the system composed of the pseudoscalar and scalar charmed mesons. The S-wave $D\bar{D}_0(2400) + h.c.$ molecular charmonium appears as the molecular partner of $Y(4274)$, which is in accord with the enhancement structure appearing at 4.2 GeV in the $J/\psi\omega$ invariant mass spectrum from $B$ decays. Our study shows that the enhancement structures, *i.e.*, the newly observed $Y(4274)$ and the previously announced $Y(4140)/Y(3930)$ in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra, can be understood well under the uniform framework of the molecular charmonium, which can be tested by future experiments.

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Very recently the CDF Collaboration [1] studied the $J/\psi\phi$ invariant mass spectrum in the $B \to J/\psi\phi K$ channel based on the sample of $p\bar{p}$ collision data with an integrated luminosity of 6 fb$^{-1}$. Besides confirming the previous $Y(4140)$ state [2], CDF also reported the observation of an explicit enhancement structure with $3.1\sigma$ significance in the $J/\psi\phi$ invariant mass spectrum, which is of mass $M = 4274.4^{\pm 8.4}_{-6.7}$(stat) MeV and width $\Gamma = 32.3^{+21.9}_{-15.3}$(stat) MeV [1]. We will refer to this new structure by the name $Y(4274)$ in this letter.

The appearance of $Y(4274)$ in the $J/\psi\phi$ invariant mass spectrum not only makes the charmonium-like family abundant, but also raises our interest in exploring the origin of enhancement structures in the $J/\psi\phi$ invariant mass spectrum and revealing the relation between $Y(4274)$ and $Y(4140)$, which will be helpful to improve our knowledge of the underlying properties of charmonium-like state.

The previous observation of $Y(4140)$ has stimulated great interest among theorists, especially when associating it with $Y(3930)$ reported by the Belle Collaboration [3] and confirmed by the BaBar Collaboration [4]. Both $Y(4140)$ and $Y(3930)$ were observed in the mass spectrum of $J/\psi$ + *light vector meson* in $B$ meson decay

$$B \to K + \left\{ \begin{array}{l} \underline{J/\psi\phi} \;\Longrightarrow Y(4140) \\ \underline{J/\psi\omega} \;\Longrightarrow Y(3930) \end{array} \right. .$$

Generally in the weak decays of $B$ meson, the $c\bar{c}$ pair creation mainly results from the color-octet mechanism. Furthermore, a color-octet $q\bar{q}$ pair is easily popped out by a gluon.

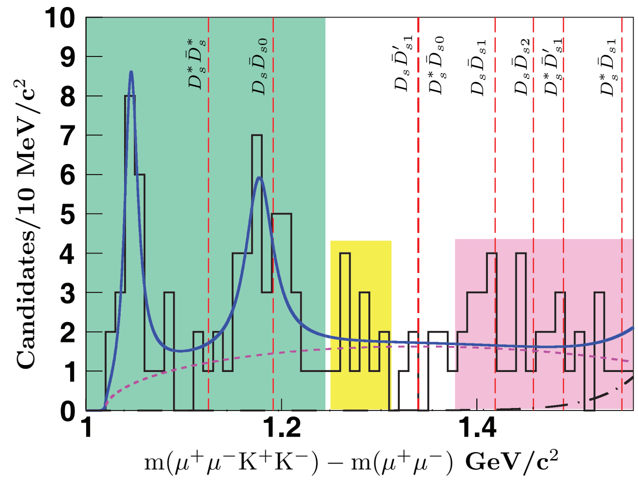


FIG. 1: (Color online.) The mass difference $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution (histogram) for events in the $B^+$ mass window [1]. Besides $Y(4140)$, one explicit enhancement appears around 4274 MeV. Here, the purple dashed line is the background from the three-body phase space. The blue solid line is the fitting result with resonance parameters of $Y(4140)$ and $Y(4270)$ resonances in Ref. [1]. The vertical red dashed lines denote the thresholds of $D_s^*\bar{D}_s^*$, $D_s\bar{D}_{s0}(2317)$, $D_s\bar{D}'_{s1}(2460)$, $D_s^*\bar{D}_{s0}(2317)$, $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$.

Thus, $c$ and $\bar{c}$ capture $\bar{q}$ and $q$ respectively to form a pair of charmed mesons. By this mechanism, a pair of the charm-strange mesons with the low momentum easily interact with each other and even form the molecular charmonium. Additionally, $Y(4140)$ and $Y(3930)$ are close to the thresholds of $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ respectively, and satisfy an almost exact mass relation

$$M_{Y(4140)} - 2M_{D_s^*} \approx M_{Y(3930)} - 2M_{D^*}. \tag{1}$$

The mass difference between $Y(4140)$ and $Y(3930)$ is approximately equal to that between $\phi$ and $\omega$ mesons: $M_{Y(4140)} -$

*Corresponding authors.
‡Corresponding authors.
†Electronic address: xiangliu@lzu.edu.cn
§Electronic address: zhusl@pku.edu.cn

$M_{Y(3930)} \sim M_\phi - M_\omega$. The peculiarity of $B \to K(c\bar{c})$ and the similarity between $Y(4140)$ and $Y(3930)$ provoke an uniform molecular charmonium picture to reveal the underlying structure of $Y(4140)$ and $Y(3930)$ [5, 6]. Applying $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ molecular structures to explain $Y(4140)$ and $Y(3930)$ respectively not only solves a long-standing puzzle of the structure of $Y(3930)$, but also opens a window to investigate the hadron dynamics of exotic state beyond the conventional $q\bar{q}$ and $qqq$ states. A series of research work related with $Y(4140)$ were carried out later [5–19].

In Fig. 1, we present the comparison between the experimental data [1] and the thresholds of the charmed-strange meson pairs. $Y(4274)$ is just below the threshold of $D_s\bar{D}_{s0}(2317)$ similar to the situation of $Y(4140)$, which stimulates us to deduce naturally that $Y(4274)$ enhancement results from an S-wave $D_s\bar{D}_{s0}(2317)+h.c.$ molecular system $Y^{s\bar{s}}$ with the flavor wave function

$$|Y^{s\bar{s}}\rangle = \frac{1}{\sqrt{2}}\Big[|D_s^+D_{s0}^-\rangle + |D_s^-D_{s0}^+\rangle\Big]. \quad (2)$$

The $C$ parity of the isoscalar $Y(4274)$ is positive due to the $Y(4274) \to J/\psi\phi$ decay mode observed by CDF. As the cousin of $Y^{s\bar{s}}$, $Y^{u\bar{u}/d\bar{d}}$ is of the flavor wave function

$$|Y^{u\bar{u}/d\bar{d}}\rangle = \frac{1}{2}\Big[|\bar{D}_0^0D^0\rangle + |D_0^0\bar{D}^0\rangle + |D_0^-D^+\rangle + |D_0^+D^-\rangle\Big]. \quad (3)$$

For such S-wave pseudoscalar-scalar systems, their quantum number must be $J^P = 0^-$. Performing dynamical investigations of $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ can answer whether there exist $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ molecular systems, which is one of the main tasks of this letter. What is more important is that understanding the underlying structure of $Y(4274)$ will be helpful for revealing the properties of $Y(4140)$ [5, 6] taking into account the similarities between $Y(4274)$ and $Y(4140)$.

Using the effective Lagrangian in the heavy meson chiral perturbation theory (HM$\chi$PT) [20, 21] and the method developed in literature [23], we obtain the effective potentials of $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ states [24]

$$\mathfrak{V}_{eff}^{s\bar{s}}(r) = V_\phi^{Direct}(r) + \frac{2}{3}V_\eta^{Cross}(r), \quad (4)$$

$$\mathfrak{V}_{eff}^{u\bar{u}/d\bar{d}}(r) = \frac{3}{2}V_\rho^{Direct}(r) + \frac{1}{2}V_\omega^{Direct}(r) + V_\sigma^{Direct}(r) + \frac{3}{2}V_\pi^{Cross}(r) + \frac{1}{6}V_\eta^{Cross}(r). \quad (5)$$

Here, the subscript of the sub-potential denotes the exchanged light meson. The general expressions of the sub-potentials corresponding to the pseudoscalar, sigma and vector meson exchanges are

$$V_V^{Direct}(r) = -\frac{\beta\beta'}{2}g_V^2 Y(\Lambda, q_0 = 0, m_V, r), \quad (6)$$

$$V_\sigma^{Direct}(r) = -g_\sigma g'_\sigma Y(\Lambda, q_0 = 0, m_\sigma, r), \quad (7)$$

$$V_P^{Cross}(r) = \frac{h^2 {q'_0}^2}{f_\pi^2} Y(\Lambda, q'_0, m_P, r), \quad (8)$$

where $f_\pi = 132$ MeV and $g_V = m_\rho/f_\pi = 5.8$. $g_V$, $h$, $\beta^{(\prime)}$, $g_\sigma^{(\prime)}$ are the parameters in the effective Lagrangian, which describe the interaction of the heavy flavor mesons with the light mesons [21]. $q'_0$ is taken as $m_{D_{s0}} - m_{D_s}$ and $m_{D_0} - m_D$ for $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$, respectively. And the $Y$ function is

$$Y(\Lambda, \kappa, m, r) = \begin{cases} \text{if } |\kappa| \leq m, & -\frac{1}{4\pi r}\left(e^{-\zeta_1 r} - e^{-\zeta_2 r}\right) + \frac{1}{8\pi}\frac{\zeta_2^2-\zeta_1^2}{\zeta_2}e^{-\zeta_2 r} \\ \text{otherwise}, & -\frac{1}{4\pi r}\left(\cos(\zeta'_1 r) - e^{-\zeta_2 r}\right) + \frac{1}{8\pi}\frac{\zeta_2^2+\zeta_1'^2}{\zeta_2}e^{-\zeta_2 r} \end{cases}$$

with $\zeta_1 = \sqrt{m^2-\kappa^2}$, $\zeta'_1 = \sqrt{\kappa^2-m^2}$ and $\zeta_2 = \sqrt{\Lambda^2-\kappa^2}$. $\Lambda$ is the cutoff to cure the singularity of the effective potential.

In Fig. 2, one presents the line shapes of the potentials listed in Eqs. (4) and (5). For $Y^{s\bar{s}}$, the exchange potential of the $\phi$ meson can be ignored compared with that of the $\eta$ meson. The total effective potential of $Y^{s\bar{s}}$ is dominated by the $\eta$ exchange potential. For $Y^{u\bar{u}/d\bar{d}}$, the $\pi$ meson plays an important role especially in the range of $r > 5\,\text{GeV}^{-1}$ since the exchange potentials of $\rho$, $\omega$, $\sigma$ and $\eta$ decay exponentially with $r$. The behavior of the potential depicted in Fig. 2 indicates that we only need to consider the $\eta$ meson exchange potential for $Y^{s\bar{s}}$ and the $\pi$ meson exchange potential for $Y^{u\bar{u}/d\bar{d}}$ when finding the bound state solution by solving Schrödinger equation. Furthermore, whether there exist bound state solutions for $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ systems is closely related to the corresponding strengths of the $D_{s0}(2317)D_s\eta$ and $D_0(2400)D\pi$ couplings.

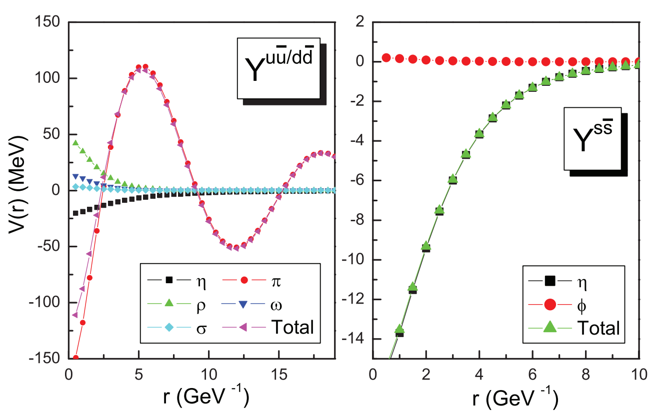


FIG. 2: (Color online.) The potentials of $Y^{s\bar{s}}$ (right-side diagram) and $Y^{u\bar{u}/d\bar{d}}$ (left-side diagram) with typical value $\Lambda = 1$ GeV. Here, we take $\beta = 0.9$, $\beta' = 1$, $g_\sigma = g'_\sigma = -0.76$, $h = -0.56 \pm 0.28$ following Refs. [21, 22].

In Fig. 3, we show the variation of the numerical result of the bound state solutions for $Y^{s\bar{s}}$ with the values of $h$ and $\Lambda$, which indicates that there indeed exists a $D_{s0}(2317)\bar{D}_s + h.c.$ molecular charmonium corresponding to newly observed enhancement $Y(4274)$. Our numerical results overlap with the mass difference ($\sim -11$ MeV) between $Y(4274)$ and the threshold of $D_{s0}(2317)\bar{D}_s$. The corresponding cutoff $\Lambda$ lies in a reasonable range which is expected to be around 1-3 GeV.

We also find that the larger $|h|$ values make the corresponding $\Lambda$ become smaller, *i.e.*, $\Lambda$ tends to be around 1 GeV, which is fully consistent with the expected behavior of the potential of the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ system.

Besides supporting the assignment of $Y(4274)$ as the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular state, our dynamical calculation also provides a novel approach to extract the $h$ parameter, which encodes the important information of the $D_{s0}(2317)D_s\eta$ interaction and the underlying properties of $D_{s0}(2317)$ [25]. This coupling can not be extracted experimentally since the $D_{s0}(2317) \to D_s\eta$ decay is forbidden kinematically. Our result indicates that the $|h|$ value corresponding to the binding energy of the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ system consistent with mass difference ($\sim -11$ MeV) is in the range $1.2 \sim 1.5$ associated with reasonable $\Lambda$ value, which can be confirmed by further theoretical study.

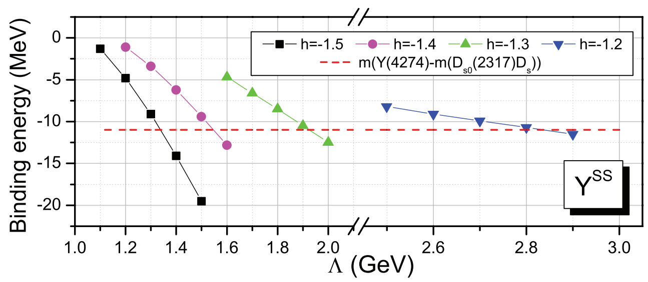


FIG. 3: (Color online.) The obtained bound state solutions of $Y^{s\bar{s}}$ system dependent on $h$ values and $\Lambda$. Here, we also compare our result with the mass difference (red dashed line) between $Y(4274)$ and the threshold of $D_{s0}(2317)D_s$.

We extend the same formalism to the $Y^{u\bar{u}/d\bar{d}}$ system, where input parameter $h$ for the $D_0(2400)D\pi$ coupling is constrained by the decay width of the $D_0(2400) \to D\pi$ to be $h = -0.56 \pm 0.2$ [21]. The binding energy of the $Y^{u\bar{u}/d\bar{d}}$ system is $-9.85$, $-10.11$, $-10.23$, $-10.30$, $-10.34$, $-10.38$, $-10.42$ MeV corresponding to the typical value of $\Lambda = 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5$ GeV, where the bound state solution of the $Y^{u\bar{u}/d\bar{d}}$ system is insensitive to $\Lambda$, which indicates the existence of the molecular cousin of the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular state, *i.e.*, an S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium. Thus, finding the evidence of S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium can provide important support to the assignment of $Y(4274)$ as an S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular state. The important hidden-charm decay mode of the S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium is $J/\psi\omega$, which is the same as in the case of $Y(3930)$ [3, 4].

From the published experimental data of the $J/\psi\omega$ invariant mass spectrum [3, 4], we indeed notice an enhancement structure around 4.2 GeV just below the threshold of the $D_0(2400)\bar{D}$ pair as illustrated in Fig. 4, which is amazingly consistent with our prediction of the S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium. We expect further high-statistics measurement from future experiments to test our prediction of the S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium.

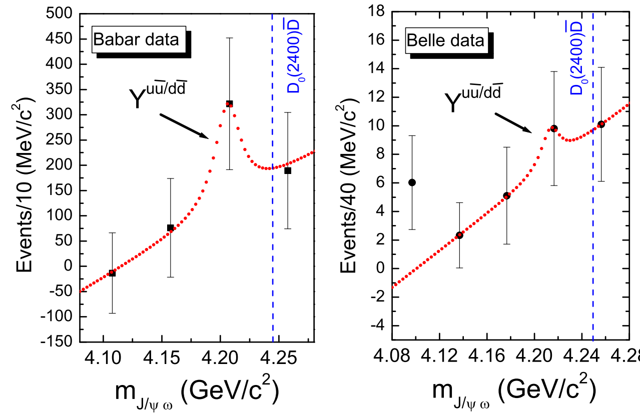


FIG. 4: The $J/\psi\omega$ invariant mass spectrum in the $B \to J/\psi\omega K$ decay announced by the Belle Collaboration [3] and the Babar Collaboration [4]. Here, the vertical blue dashed line denotes the threshold of $D_0(2400)\bar{D}$. The red dotted line is the fitting result.

The S-wave $D_s0(2317)\bar{D}_s/D_0(2400)\bar{D}$ molecular state with spin-parity $J^P = 0^-$ does not couple to the $D\bar{D}/D_s\bar{D}_s$ channels, which is strictly forbidden by the conservation of the parity and angular momentum. In addition, the S-wave $D_s0(2317)\bar{D}_s/D_0(2400)\bar{D}$ molecular state may couple to the $D^*\bar{D}/D_s^*\bar{D}_s$ and $D^*\bar{D}^*/D_s^*\bar{D}_s^*$ via P-wave, which is expected to be suppressed compared to the S-wave mode. Due to the above reasons, the coupled-channel effect on the S-wave $D_s0(2317)\bar{D}_s/D_0(2400)\bar{D}$ molecular state may be weak, which is ignored in this work.

As an S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular charmonium with $J^P = 0^-$, the decay modes of $Y(4274)$ include the hidden-charm decay mode $J/\psi\phi$ observed by CDF [1], the two-body P-wave open-charm decays $D_s\bar{D}_s^* + h.c.$ and $D_s^*\bar{D}_s^*$, the radiative decay $D_s^*\bar{D}_s\gamma + h.c.$, and the iso-spin violating three-body strong decay $D_s\bar{D}_s\pi^0$ via the $\eta - \pi^0$ mixing mechanism [2, 3]. Similarly $Y^{u\bar{u}/d\bar{d}}$ can decay into $J/\psi\omega$, $D\bar{D}^* + h.c.$, $D^*\bar{D}^*$, $D\bar{D}\pi$, $D^*\bar{D}\gamma + h.c.$ etc.

After figuring out the underlying structure of $Y(4274)$ and predicting its molecular cousin, we notice that there exist two event clusters around the ranges of $\Delta M \sim 1.27$ GeV and $1.4 < \Delta M < 1.5$ GeV marked by yellow and pink in Fig. 1, if we focus on the remaining CDF's data corresponding to $\Delta M > 1.24$ GeV. If these two event clusters are confirmed by future experiments, we might also try to understand them under the same framework of the molecular charmonium. Basing on the present low-statistic data [1], we speculate that the structure appearing at $\Delta M \sim 1.27$ is related to the $D_s\bar{D}'_{s1}(2460)$ or $D_s^*\bar{D}_{s0}(2317)$ system. The other one in the range $1.4 < \Delta M < 1.5$ GeV may result from the $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$ systems since the event cluster in the range $1.4 < \Delta M < 1.5$ GeV just overlaps with the corresponding thresholds (see Fig. 1 for more details). One may recall the similar situation before finding

the evidence of $Y(4274)$ by CDF [1]. The CDF's data with an integrated luminosity of 2.7 $\text{fb}^{-1}$ reported in Ref. [2] only displayed the event cluster at 4.27 GeV besides the evidence of $Y(4140)$. Confirming the above speculation by further experimental study of $J/\psi\phi$ invariant mass spectrum from $B$ decay will not only test the molecular charmonium assignments of $Y(4140)$ and $Y(4274)$, but also improve our understanding of the line shapes appearing at hidden-charm invariant mass spectra.

In summary, the newly observed structure $Y(4274)$ in the $J/\psi\phi$ invariant mass spectrum is first interpreted as the S-wave $D_s\bar{D}_{s0}(2317) + h.c.$ molecular charmonium well from the dynamical study of the system composed of the pseudoscalar and scalar charmed mesons. Furthermore, we predict the S-wave $D\bar{D}_0(2400) + h.c.$ molecular charmonium appearing as the cousin of $Y(4274)$, which is consistent with the enhancement structure around 4.2 GeV in the $J/\psi\omega$ invariant mass spectrum from $B$ decay [2, 3]. Thus, the enhancement structures including the present $Y(4274)$, the previous $Y(4140)$ and $Y(3930)$ observed in the $J/\psi\phi$ [1, 2] and $J/\psi\omega$ [2, 3] invariant mass spectra respectively, can be accommodated well in the uniform framework of the molecular charmonium. In addition, we find two possible event clusters in the $J/\psi\phi$ invariant mass spectrum might related to the molecular charmonia, which can be tested by high-statistic experimental data in future experiment.

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